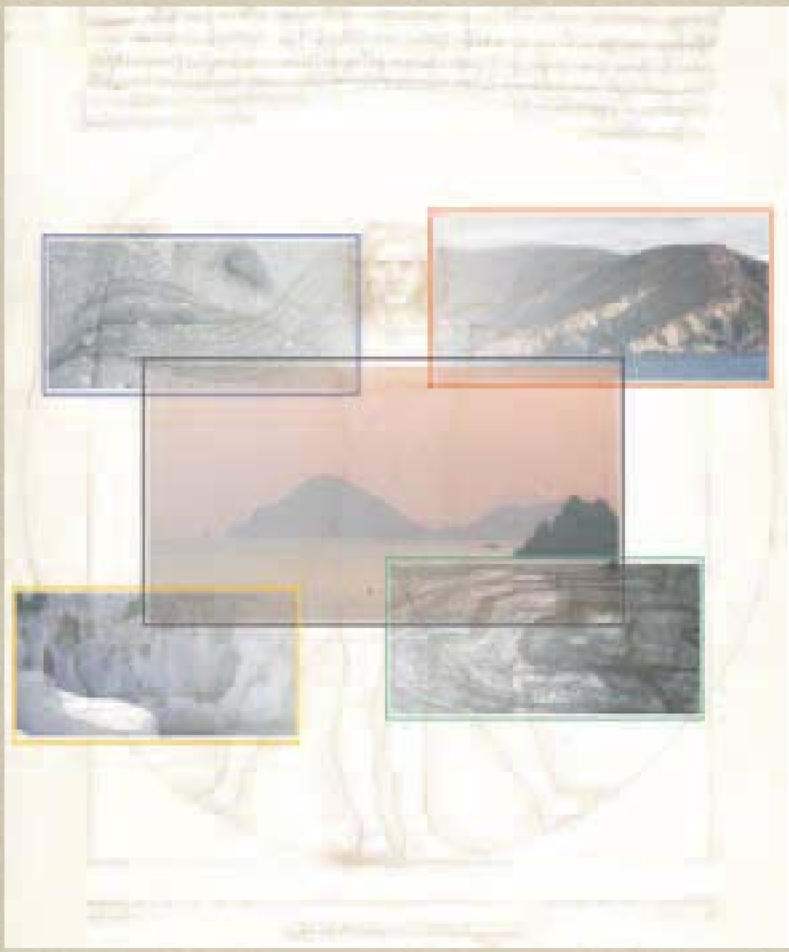
Field Trip Guide Book - P70

Volume n°6 - from P55 to PW06

32nd INTERNATIONAL GEOLOGICAL CONGRESS

A CRUSTAL SECTION THROUGH INTRUSIVE AND EFFUSIVE VOLCANIC COMPLEXES OF THE TUSCAN MAGMATIC PROVINCE (CENTRAL ITALY)



Leader: G. Poli

Florence - Italy
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A CRUSTAL SECTION THROUGH INTRUSIVE AND EFFUSIVE VOLCANIC COMPLEXES OF THE TUSCAN MAGMATIC PROVINCE (CENTRAL ITALY)

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Front Cover:
Center: Sunset on Capo Enfola.
Top left: Interplay between brittle and plastic behavior of the intruding dyke and the host Sant'Andrea crystal mush.
Top right: Oriented cliff bounding to the north the gulf of Marina di Campo.
Bottom right: Ductile deformation in carbonate layers at Spartaia.
Bottom left: General view of Sant'Andrea outcrop.

Leader: G. Poli

Introduction

The Tuscan Magmatic Province (TMP) is an outstanding natural laboratory for understanding geological and structural features related to the emplacement of plutonic and volcanic complexes, and to study dynamical and geochemical mechanisms acting during interaction between mantle derived and crustal melts. TMP is, in fact, constituted by a series of intrusive and extrusive centers scattered through southern Tuscany, the Tuscan archipelago, and northern Latium, in which several types of magmas coexist. These include crustal anatectic acidic peraluminous rhyolites and granites, and a wide range of mafic to intermediate magmas, including high-potassium calcalkaline, shoshonitic, potassic and ultrapotassic lamproitic rocks.

The aim of the field trip is to provide a crustal section of the Tuscan Magmatic Province from Miocene to Pleistocene. It will be focused on: i) magmatic structures in granitoids that are among the youngest intrusive rocks on Earth (<7Ma); ii) shallow level felsic intrusions representing an spectacular example of multilayer laccolith complex; iii) occurrence of intrusive and effusive rocks of similar composition and age; iv) occurrence of cordierite-bearing rocks both in intrusive and effusive environment; v) occurrence of impressive evidence of magma mixing/mingling in granitoids and volcanics rocks; vi) field studies of compositional diversity of magmatism versus source rocks; vii) field discussions on crustal melting and origin of silicic melts. The variability of mantle- derived and crust-derived magmas coexisting in space and time in the Tuscan Magmatic Province will provide, in addition, the basis for deep discussions about possible end-members involved in the interaction processes, also in relationship with the evolving geodynamic setting of the region from Miocene to Recent. The Tuscan Magmatic Province is also known for ore deposits that have been exploited for three millennia, and contributed to focus civilisation in this part of the Mediterranean Sea since Etruscan times.

The field trip is organized starting with an excursion on the pluton and the laccoliths of Elba Island, continuing with granitoid masses constituting the Islands of Montecristo and Giglio, and then focusing the final part of the field trip on volcanic rocks cropping out in the area of San Vincenzo and Roccastrada.Text

Regional geologic setting

The present-day geological framework of the Italian peninsula, as well as that of the Peri-Mediterranean regions, is mainly the result of a complex paleogeographical and geodynamical evolution related to the opening and successive closure of the Tethys Ocean. The present organisation is due to active collision between the African and the European blocks. Convergence between these two major plates led to the formation of important orogenic belts all around the Mediterranean area (fig. 1). While Africa and Europe converged, the smaller blocks of the Mediterranean region (e.g. the Adria plate) were subjected to rigid trailing translations and/or rotations. This explains the variety of kinematic processes presently occurring, including lithospheric subduction, back-arc spreading, strike-slip faulting and lateral expulsion of lithospheric blocks. Continental collision of the Adria and European plates was active since Eocene times, when the subduction of oceanic crust under the European continent was completed forming a double-vergent orogenic belt.

The Neogene paleogeographic and paleotectonic evolution of the Italian peninsula is principally influenced by the evolution of the Apenninic orogen related to a west dipping subduction connected to the back-arc opening of the Provençal Basin (west of the Corsica-Sardinia block) during Oligocene-Early Miocene times. The Apenninic orogen was characterised by a rapid eastward shift of both foredeep and chain areas, and by the contemporaneous collapse of the inner side of the chain. Coeval with, and related to the migration of the foredeeps, was the contemporaneous migration of the W-dipping subduction zone to the east of the Corso-Sardinian block, which started its counter-clockwise rotation around the Oligocene-Lower Miocene boundary. Subduction of the Adria plate was accompanied by Late Oligocene-Middle Miocene calc-alkaline volcanism in western Sardinia. Foreland migration and subsidence are expression of the same mechanism, that is of the eastward roll-back of the subducting plate.

From the Late Tortonian to Messinian p.p., extensional tectonics began in the northern Tyrrhenian area, with formation of fluvio-lacustrine and paralic environments, and in the western part of the southern Tyrrhenian Sea. Oceanic crust formed in limited portions of the southern Tyrrhenian Basin. From Late Messinian to late Pliocene p.p., a new

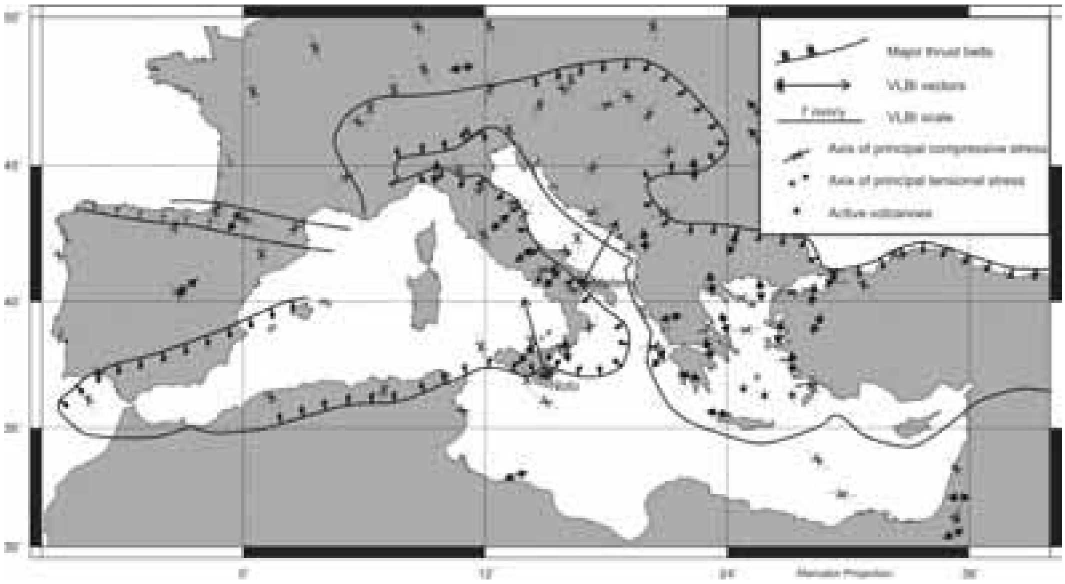

Figure 1 - Earthquake distribution and present regional stress field in the Mediterranean area.

system of extensional faults dissected the eastern portion of the previously rifted northern Tyrrhenian Basin and the western margin of the Apenninic belt. From the late Pliocene p.p. up to Quaternary time extension continued, forming intramontane basins all along the internal margins of the northern and central Apennines. The present-day thinned crust is the result of a crustal attenuation started in Middle Miocene in the Corsica basin that continued during the Late Miocene-Middle Pliocene in Tuscany, allowing post-orogenic basins to form. Extension, and the accompanying uplift reached internal Umbria in the Late Pliocene. This process is still continuing in the axial zone of the Umbria-Marche Apennines. Extension migrated from west to east in the same way compression did, so that while western sectors of Apennines were subjected to extension, thrusts were acting in Adriatic area. In this scheme the shallow Moho detected by the CroP-03 seismic line on the Tuscan and western Umbria regions could be interpreted as a "new" moho resulting from a thinning processes of a previously thicker crust.

From Middle Pliocene times, western Tuscany underwent an almost generalized and strong regional surface uplift still active today. This was caused by an astenospheric uplift that thinned the crustal stack and completely restructured the crust-mantle boundary. As a result a new Moho formed underneath the Tuscan area. At this stage, and in response to the uplift, the mantle underwent partial melting to generate basaltic magmas that either erupted or interacted with crustal anatectic melts generating the wide spectrum of basic-acid associations constituting the Tuscan Magmatic Province.

Magmatism in Central-Southern Italy

Central-Southern Italy is a geologically complex area in which a wide range of Recent magma types, from tholeiitic to Na- and K-alkaline, are closely associated in space and time. This variable magmatic setting reveals compositionally complex mantle sources. Potassic and ultrapotassic magmatism is one of the most striking and typical geological features of the Tyrrhenian side of the Italian peninsula. Extensive petrologic and geophysical studies reveal the occurrence of a large number of compositionally distinct magmatic zones, with specific petrological and/or geochemical characteristics: Tuscany province, Roman province, Umbria ultra-alkaline province, Ernici-Roccamonfina province, Neapolitan-Eastern Aeolian Arc province, Aeolian arc province, Mount Vulture, Na-alkaline volcanoes of Etna, Iblei, Ustica and the Sicily channel (Linosa, Pantelleria).

The overall picture that unfolds from petrological and geochemical data is that the variety of magmas reflects a mosaic of compositionally distinct pre-metasomatic mantle sources that were modified by

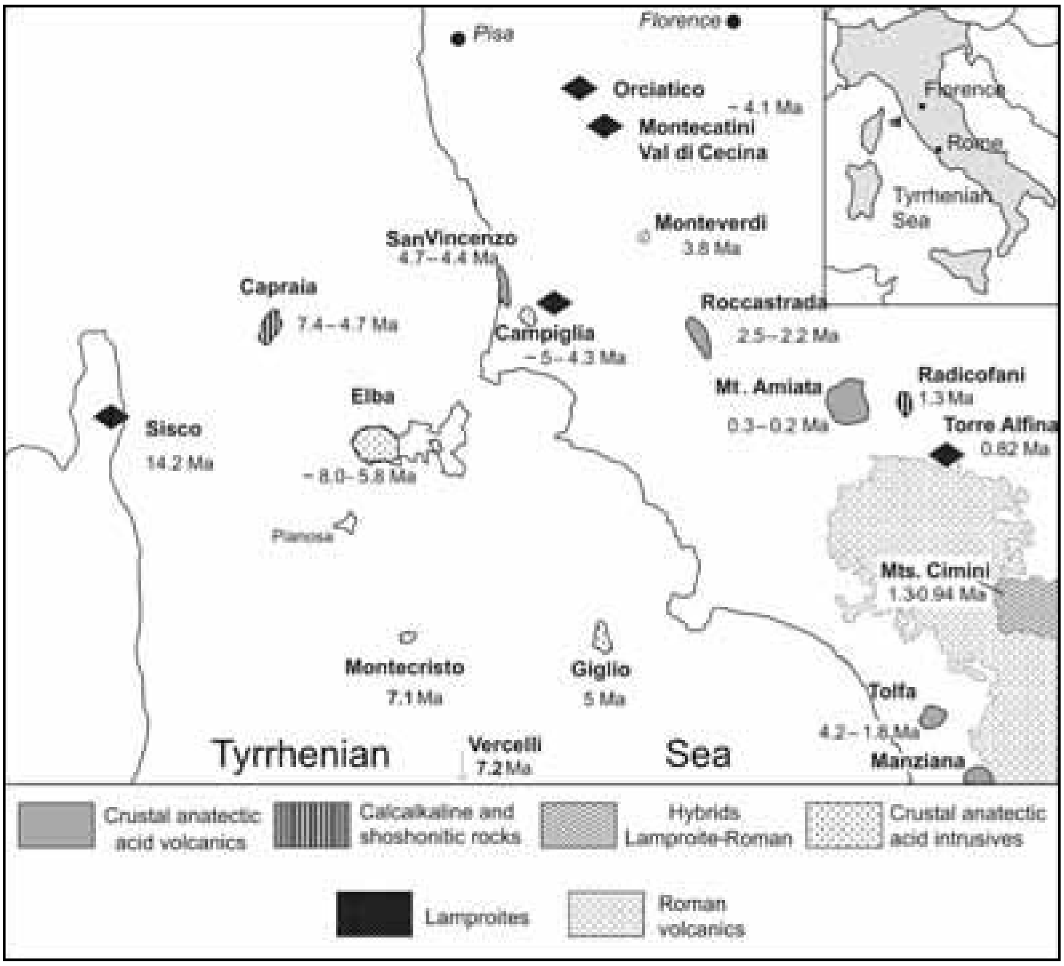

Figure 2 - Location, age and compositional characteristics of intrusive and extrusive rocks of the Tuscan magmatic province. Note the younging of magmatism from west to east.

different metasomatic events. There is a wide, though not undisputed, consensus that the source zones for the largest part of the magmatism were affected by metasomatic modification by fluids or melts released by subducting plates. Trace element and isotope data on mafic volcanic rocks suggest the occurrence of at least three compositionally distinct metasomatic events, which likely occurred at different times and generated a variably metasomatized upper mantle beneath the Italian peninsula. The oldest event is at least Alpine in age and affected the upper mantle beneath the Tuscany province. Metasomatism in the other districts is younger and is probably related to west- and northwest-dipping subduction zones of the Adria plate and the Ionian sea.

The Tuscan Magmatic Province

The Tuscan magmatic province consists of a series of intrusive and extrusive centres scattered through southern Tuscany and the Tuscan archipelago. The acid centres of the Tolfa-Cerveteri-Manziana area, northwest of Rome, are also traditionally included into the Tuscany province. Figure 2 gives an overview of locations, ages and main compositional characteristics of the Tuscany magmatism. Magmatic rocks consists of stocks, dykes, necks, lava flows and domes, and of the large volcanic edifices of Monte Amiata, Monti Cimini and Capraia Island. Ages range from 8-7 Ma to 0.2 Ma, and show a tendency to decrease from west to east. An outcrop of lamproitic rocks at Sisco (Corsica) has an age of about 14 Ma, and is also considered to

belong to the Tuscan magmatic province.
The basement rocks in Tuscany consist of metamorphic terrains overlain by various allochthonous and autochthonous sequences. The thickness of the continental crust is moderate, and reaches a minimum beneath the Tyrrhenian border of southern Tuscany, where the Moho occurs at a depth of about 25 km. This reveals a mantle doming beneath southern Tuscany. Heat flow is high, as testified by the occurrence of well known geothermal fields at Larderello. An important geophysical feature of southern Tuscany is given by a zone of low seismic velocities within the upper mantle. This has been interpreted as due to the occurrence of a layer with a crustal-type density. There is debate on the physical nature of this layer, which has been suggested to represent either an upper crustal slice within the upper mantle (crustal doubling), or partially molten mantle material (e.g., metasomatic veins). Therefore, southern Tuscany magmatism appears to be associated with thin crust, high heat flow and mantle doming (asthenospheric uplift). High velocities of S-waves (up to 4.6 km/s) in the northern-central Apennine area, below a depth of about 70 km suggest the presence of deep-seated lithospheric roots, which are almost vertical. These roots have been interpreted to represent the relict of a downgoing lithospheric slab.

The Tuscan Magmatic Province is very complex including crustal anatectic acid peraluminous rhyolites and granites, and a wide range of mafic to intermediate magmas, including high-potassium calcalkaline, shoshonitic, potassic alkaline and ultrapotassic lamproitic rocks. Mixing appears to have affected both mafic and acid rocks; the latter bear textural (mafic enclaves, xenocrysts, etc.) and geochemical evidence of mingling and mixing with various types of mantle-derived calcalkaline to potassic melts.

Acid rocks in the Tuscany province occur as lavas at San Vincenzo, Roccastrada, Monte Amiata and Monti Cimini, and as intrusive bodies at Elba, Montecristo, and Giglio islands, and at Gavorrano and Campiglia. Other granite bodies occur as seamounts in the northern Tyrrhenian sea (Vercelli), and as hidden intrusions encountered by drilling. Notably, pyroclastic rocks are scarce or absent, except at Mt. Cimini and Tolfa where ignimbrites are present. The acid rocks, except for Roccastrada rhyolites, are associated with variable amounts of mafic material, represented mainly by blobs of mafic melts intruded into and mingled with the acid host magma.

Mafic rocks from Tuscany have variable degree of enrichment in alkalies, especially potassium, from high potassium calcalkaline and shoshonitic to potassic and ultrapotassic types. These define continuous trends that straddle the boundary between potassic rocks with lamproitic affinity, and Roman-type high potassium and potassic rocks. Rocks with lamproitic composition occur at Montecatini Val di Cecina, Orciatico, Torre Alfina and Sisco (fig. 2). A few dikes at Campiglia also show lamproitic affinity, although deuteric transformation has strongly modified pristine composition. Calc-alkaline and shoshonitic rocks are exposed at Capraia and Radicofani. Capraia rocks are mainly represented by lavas and scoriae, and range from high potassium calcalkaline to shoshonitic. At Radicofani shoshonitic rocks are basic to intermediate and form a large neck and some dismembered lava flows. Some rocks have intermediate compositions between lamproite and calc-alkaline-shoshonitic (or Roman-type potassium) series. The most important outcrop is found at Monti Cimini, as small olivine latite lava flows; however, also enclaves in the Monte Amiata domes, and, to some extent, Radicofani belong to this group. Incompatible element patterns resemble those of lamproites, but element concentrations (especially HFSE) are generally lower than in lamproites.

Petrological and geochemical data for mafic magmas from the Tuscan magmatic province reveal, hence, a complex evolutionary history of mantle sources. The available data suggest that at least two metasomatic events affected the lithospheric and asthenospheric mantle beneath Tuscany, generating strong vertical and lateral compositional heterogeneity. The close similarity of Tuscany lamproitic rocks with those occurring in the western Alps suggests a role of metasomatic events related to Alpine subduction processes in both areas. Younger mantle modifications occurred during subduction of the Adria plate. This was responsible for the widespread Roman magmatism, but also produced some effects in the Tuscan magmatic province, as indicated by the occurrence of hybrids of Roman-type and lamproitic magmas.

More deep general discussions on the topics reported in this brief introduction can be found in the Special Issue of Periodico di Mineralogia titled "Miocene to Recent Plutonism and Volcanism in the Tuscan Magmatic Province (Central Italy)" that will be distributed to each participant during the field excursion.

Field Trip Itinerary

Stop 1:

Capo Bianco

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Outcrops in this area are mainly constituted by the Capo Bianco intrusive unit, a low porphyritic (less than 10 vol% of quartz, K-feldspar, plagioclase and muscovite phenocrysts), peraluminous, alkali feldspar granite, that is strongly enriched in boron. The latter feature is highlighted by the widespread presence of black-blue tourmaline orbicules and spots (fig. 1 and 2).

The peculiar spotted "look" of these rocks attracted the attention of ancient people working in the Mediterranean area and a short digression about a "possible" origin of the orbicules is also included in the legend of Jason and the Argonauts, and the quest for the "Golden Fleece". On their way home the Argonauts, carrying the "Golden Fleece", crossed the Balcanic area, the Alps and, following the Rhone river they flowed into the Ligurian Sea. Out in the Ligurian, they leaved the Stoechades Islands (now Hyères islands, France) and they passed on to the island Aethalia (now Elba Island, Tyrrhenian Sea), before reaching the Greece. On Elba Island they probably visited the ematite deposits of Rio Marina area, trying to smelt some iron ore. So, "after their toil they wiped away with pebbles sweat (and ematite powder) in abundance; and pebbles like skin in colour are strewn on the beach and there are their quoits

Figure 1 Stop 1 - General view of Capo Bianco outcrop. Black tourmaline spots are dispersed within the light colored fine-grained alkali feldspar granite.

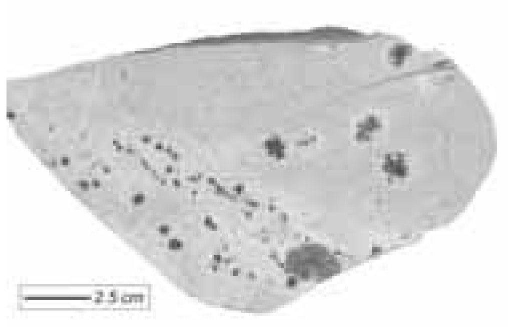

Figure 2 Stop 1 - Detail of a sample of the fine grained alkali feldspar granite containing black spots of tourmaline.

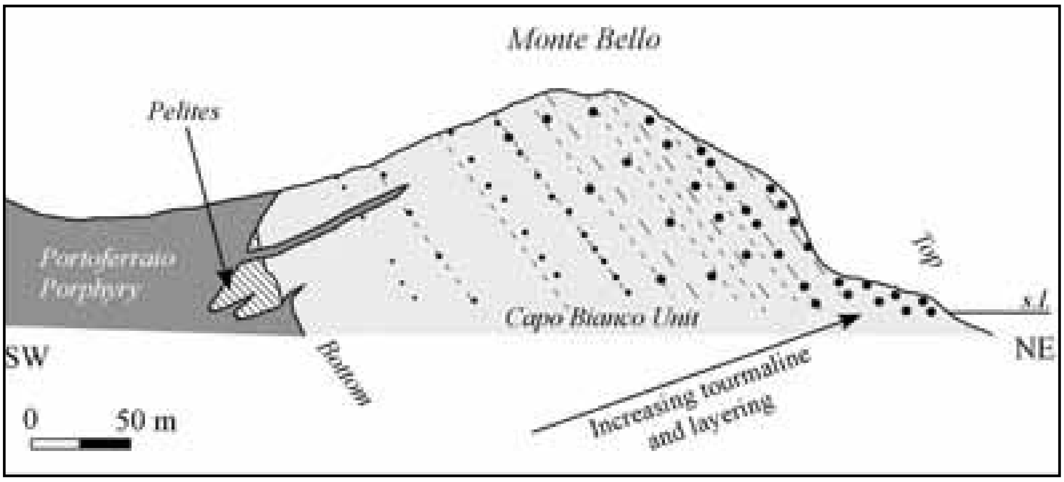

Figure 3 Stop 1 - Schematic section of Capo Bianco outcrop showing the increase of tourmaline spots size toward the top of the intrusion.

and their wondrous armour; and there is the Argoan harbour (now Portoferraio) called after them". At the present we know that the black spots in Capo Bianco are tourmalines but smelting scoria and ematite samples are easily found in this locality representing an evidence of the ancient smelting activities reported in the Mediterranean mythology.

The number and dimensions of orbicules increase from the bottom toward the top of the Capo Bianco tabular intrusion (fig. 3). Furthermore, increasing of tourmaline content is coupled with the development of a strong late magmatic layering evidenced by the distribution of tourmaline spots and muscovite flakes. All these late magmatic structures developed above the solidus (no sub-solidus deformation of crystals) and overlap the early porphyritic texture of the rocks. The later emplacement of Portoferraio porphyry and the extensional tectonics tilted the original sub-horizontal attitude of this intrusion producing the present situation where the late magmatic layering dip toward north, north-east at various degrees.

The distribution of both, tourmaline and late magmatic layering, has been attributed to the internal differentiation of the magma as B-rich fluids started to exsolve or the melt entered the immiscibility field for boron-alkali-aluminosilicate melts. Geochemical, B-isotope and fluid inclusion studies are trying to elucidate the exact evolution of processes that affected this B-rich anatectic product during its unusual subvolcanic emplacement.

Stop 2:

Cala Bardella

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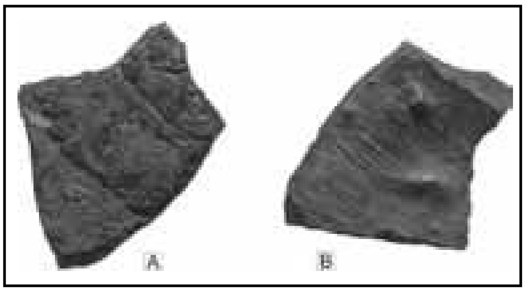
Half an hour walk from the harbour of Marina di Campo to Punta Bardella. Path across Cretaceous flysch from the village to the end of Galenzana beach. Along the shore, fist-size, black, scoriaceous, heavy slags can be found (fig. 1). These are residua from smelting furnaces of Etruscan-Roman times.

From the beach, view of several laccolih layers intruding the flysch on the opposite side of the bay of Marina di Campo (fig. 2). At the megascale the tabular intrusions are concordant with the flysch bedding. At the very tip of Punta Bardella, the contact between flysch and San Martino megacrystic porphyry is exposed (fig. 3).

No thermometamorphic effects can be detected in the host rock. The porphyry is rich in K-feldspar megacrysts up to 15 cm and quartz phenocrysts up to 2 cm (fig. 4).

K-feldspar is a high-T sanidine, testifying the magmatic origin of this mineral phase coupled with quenching of the enclosing melt. Scattered brown-altered mafic microgranular enclaves can be observed (fig. 5). The groundmass is yellow-brown due to incipient weathering.

Figure 1 Stop 2 - Sample of Etruscan-Roman smelting scoria; A) upper surface; B) bottom surface.



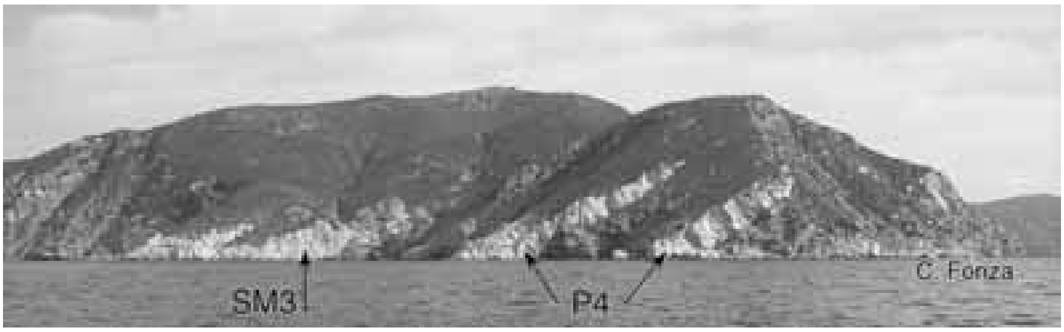


Figure 2 Stop 2 - View from the south of the WNW-ESE oriented cliff bounding to the north the gulf of Marina di Campo.

Figure 3 Stop 2 - General view of the contact between the flysch (upper part) and the megacrystic porphyry (lower part). Note K-feldspar megacrysts and quartz large crystals.

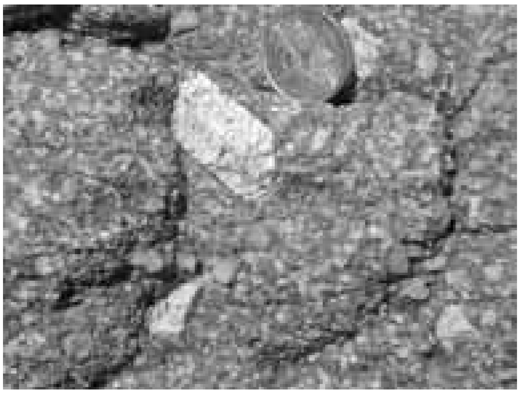


Figure 4 Stop 2 - Detailed view of the megacrystic porphyry showing the occurrence of K-feldspar megacrysts.

Figure 5 Stop 2 - Detailed view of the megacrystic porphyry containing a mafic microgranular enclave.

Stop 3:

Bontempelli Quarry
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Bontempelli quarry is one of the largest quarries within the Monte Capanne pluton. It is located immediately south of San Piero village, very close to the contact with the serpentinite country rocks which can be observed along the Marina di Campo road.
The main monzogranitic Facies (MF) in Bontempelli quarry, which is representative of the south-eastern part of the Monte Capanne pluton, is medium-grained

	Cava Bontempelli	Sant'Andrea	Pomonte
Xenolith	2.5	2.1	7.1
MME	1.4	2.6	2
K-fds megacrysts	5	110	27.5

Table 1 Stop 3 - Average number of xenoliths, MME and K-feldspar megacrysts (per m2) in Cava Bontempelli, relative to other localities in the western part of the Monte Capanne pluton. Measurements were conducted on carefully selected and statistically representative surfaces (for example, 20 m2 in Cava Bontempelli).

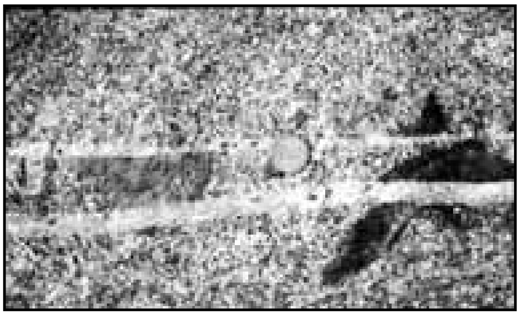

Figure 1 Stop 3 - Mafic microgranular enclave (MME, left-hand side) and metasedimentary xenolith (right-hand side) crosscut by late tourmaline-bearing aplitic veins. Note the equigranular texture and the scarcity of K-feldspar megacrysts in the San Piero Main Facies.

(2-5 mm), slightly porphyritic and homogeneous. The mineralogy chiefly consists of alkali feldspar + plagioclase + quartz + biotite ± chlorite ± tourmaline ± titanite ± apatite ± zircon ± monazite.
The modal analysis is:

Quartz	26.9%
Orthose	18.3%
Plagioclase	39.5%
Biotite and accessories	15.3%

Idiomorphic K-feldspar meagcrysts are scarce (cf. table 1) and can measure up to 5 cm long (rarely up to 9 cm long). The shape of the K-feldspar megacrysts is often irregular and hardly distinguishable from the poikilitic alkali feldspar in the matrix. When compared to the Western side of the Monte Capanne pluton, the Main Facies in San Piero displays fewer K-feldspar megacrysts and mafic microgranular enclave (MME, see table 1), while the quantity of variably digested metasedimentary xenolith is similar in both facies (table 1). Furthermore, large enclaves, which are frequently observed in the eastern side of the pluton, are conspicuously rare in the San Piero facies. However, melanocratic schlieren are locally visible and could reflect some stretching of larger disrupted enclaves. Despite the low abundance of microgranular enclaves, disequilibrium textures observed in plagioclase phenocrysts (patchy-zoning, resorption surfaces) and some K-feldspar megacrysts indicate that this facies was largely hybridised by more mafic magmas. This is also attested by the major element composition of the Bontempelli quarry main facies, whose silica content (66.9% SiO_2) is amongst the lowest recorded for the Monte Capanne MF.
Another striking feature that can be observed in Bontempelli quarry is the extensive occurrence of tourmaline-bearing aplitic veins cutting across the MF and its enclaves (fig. 1) attesting to their late injection. The main orientation of the veins is N15-N20, following the main fracture direction. Abundant tourmaline clots can also be observed along the well exposed walls of the fractures.

Stop 4:

Pomonte Quarry
Diego Perugini and Giampiero Poli
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Pomonte quarry is, together with Sant'Andrea outcrop, one of the best places to observed magma mingling/mixing phenomena in Monte Capanne pluton. The quarry shows a large and well preserved section of the pluton (fig. 1) because it was active up to recent times. Here, magma interaction processes are evidenced by extraordinary structures that can be utilized to trace the evolution of the mixing process in time and space.
Magmatic interaction structures can be divided in two main groups:

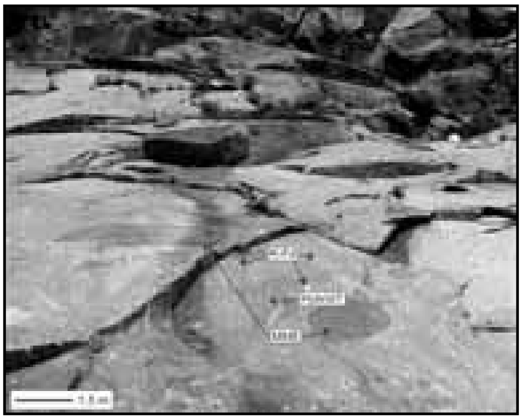

Figure 1 Stop 4 - General view of Pomonte quarry showing different magmatic interaction structures; MME=Mafic Microgranular Enclaves; Hybrid?=flow structures having a color index (mineralogical assemblage and grain size) intermediate between MME and the host granitoid mass. In the picture are also indicated K-feldspar (K-Fd) megacryts.

1) Mafic Microgranular Enclaves (MME) with different size (from 2-3 cm to 1-2 m across) and shapes dispersed in the granitoid mass (e.g. fig. 2);
2) Flow structures of the more mafic magma showing strong deformation and generating large contact surfaces with the host magma (fig. 2).
Commonly MME and flow structures contains metamorphic xenoliths (fig. 3A and B) with textures and mineralogical assemblages analogous to those occurring in the host granitoid evidencing that mass transfer processes have been active during the interaction between the mafic and felsic magmas. The same occurrence holds for K-feldspar megacrysts of the host granitoid magma that are commonly observed passing from the host magma to MME or completely inserted within MME and flow structures. In many cases the boundary between MME and host rocks is shaded and continuous making difficult to define a sharp contact between the acid and the mafic magma and evidencing that magmas underwent efficient mingling/mixing processes producing volumes of hybrid magma.
It is noteworthy that a large series of intermediate structures, in addition to the two groups discussed above, are present in the outcrop ranging from rounded MME to extremely elongated flow structures (fig. 4). Such variety of intermediate structures suggests that

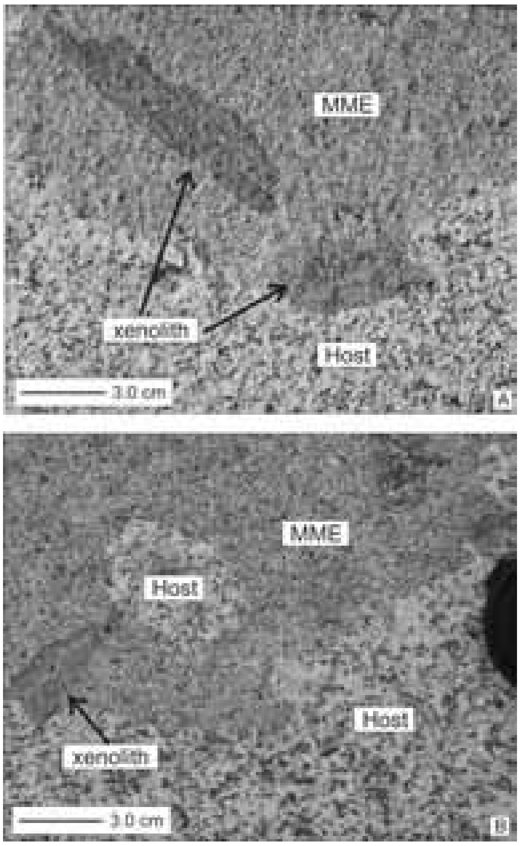

Figure 3 Stop 4 - A) Occurrence of two metamorphic xenoliths, one within a MME and the other sticking at the MME boundary; B) metamorphic xenolith passing from the host rock to the MME. The MME shown in (B) also contains a sub-spherical blob of host rock.

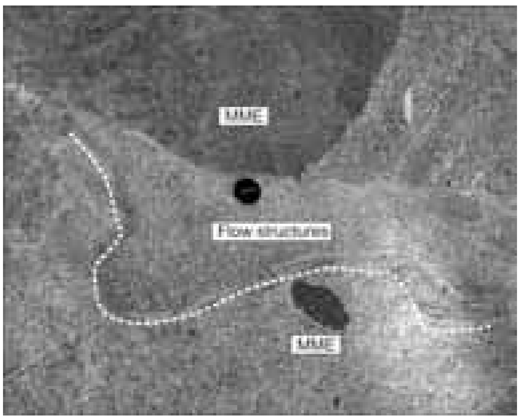

Figure 2 Stop 4 - Coexistence of Mafic Microgranular Enclaves (MME) and flow structures generated by the intimate dispersion of the mafic magma through the acid one.

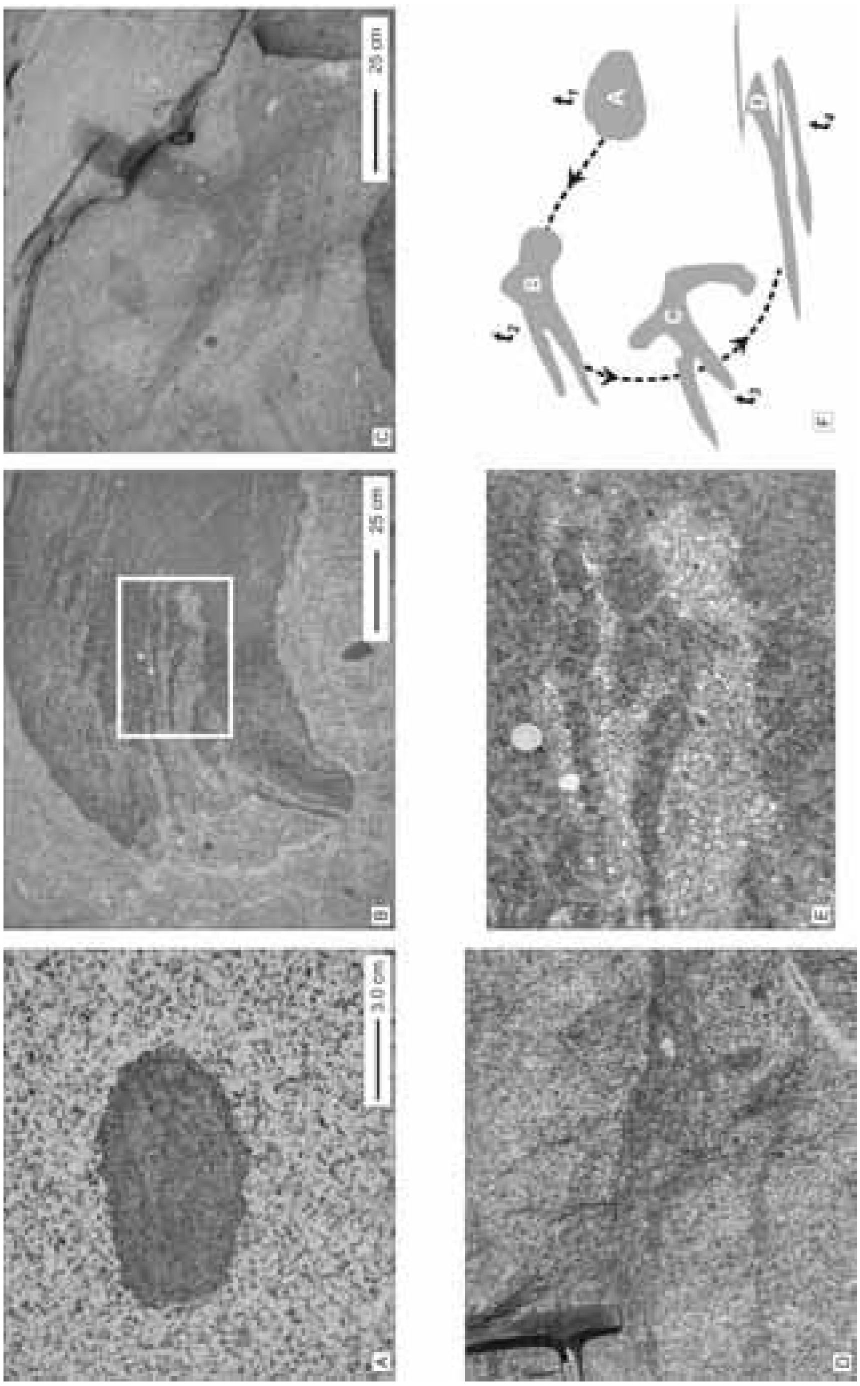

Figure 4 Stop 4. A) Example of rounded Mafic Microgranular Enclave (MME); B-D) examples of flow structures showing a progressive increase of stirring of the mafic magma inside the granitoid mass; E) magnification of portion of the picture indicated in (B) by a white square; F) hypothetical evolution of the mixing process starting from the rounded MME at time (t1) that is deformed in time (tn) by the mixing dynamics.

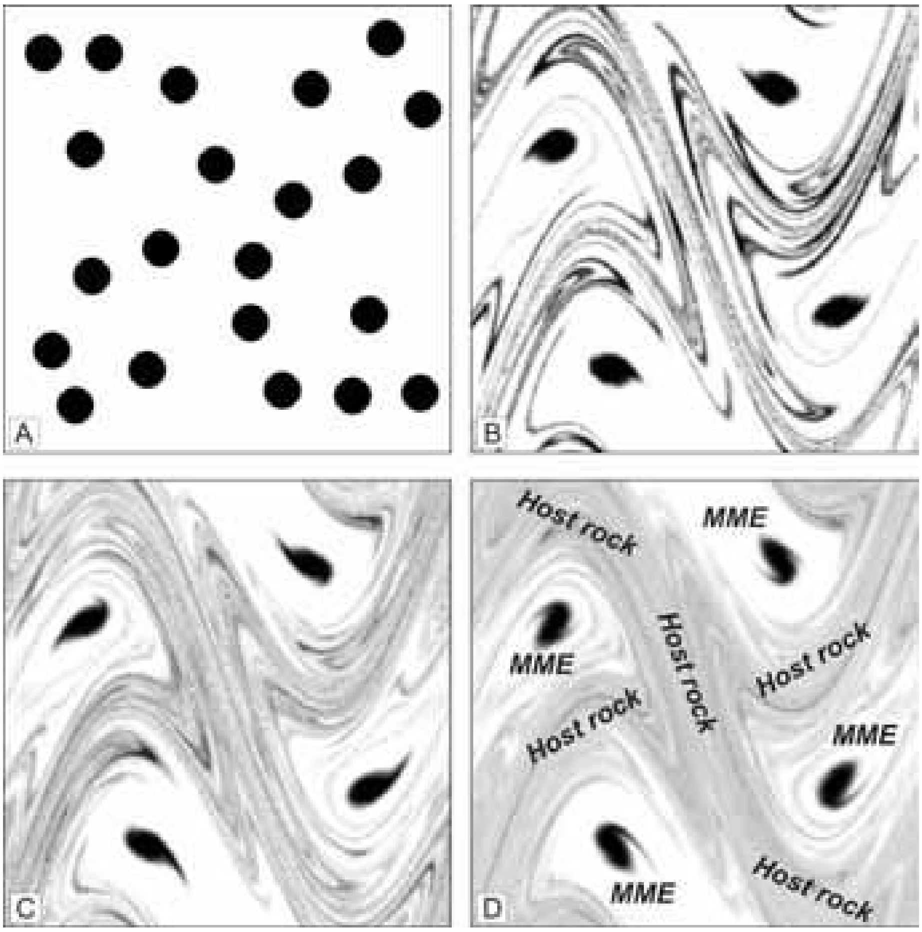

Figure 5 Stop 4 - Example of chaotic mixing system whose evolution starts from the distribution of spherical blobs of mafic magma reported in (A) and moves on in time producing the mixing systems reported in (B), (C) and (D). Note in (D) the coexistence in space and time of completely hybridised portions of magmatic system (Host rock) and unmixed or poorly mixed sub-spherical blobs of mafic magma (MME) analogous to those observed in the Pomonte quarry outcrop.

at the initial stages of the interaction process the mafic magma was dispersed through the acid one under the shape of sub-spherical blobs (fig. 4A and F) that with the passing of time (fig. 4F) suffered progressively more intense stirring (from fig. 4B to E) within the acid magma generating the observed flow structures.
However, it is to note that the outcrop, at present, shows the contemporaneous occurrence, from the metric to the micrometric length scale, of MME and flow structures (fig. 2).
The coexistence of such different structures argues against a constant rate of mingling/mixing processes. On the other hand these structures can be explained considering the contemporaneous occurrence, within the same magma mixing system, of different regions with different efficiency and coexisting in space and time (fig. 6). Such different regions, generated by chaotic dynamics, may have been responsible for the production, at the same time and at different length scales, of completely hybridised volumes of magmas coexisting with portions of the more mafic magma (MME) that did not undergo strong mixing dynamics preserving their identity for long time during the interaction process (fig. 6).
The presence of chaotic dynamics may explain most of the features observed in this outcrop starting from the presence of globular portions of little mixed mafic magma (MME) to volumes of magmas showing

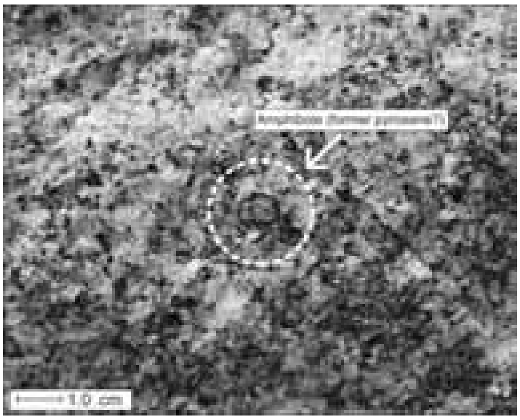

Figure 6 Stop 4 - Pseudomorphic crystal of amphibole evidenced in the picture by the dashed circle.

different degrees of hybridization.
In some cases rounded pseudomorphic crystals of amphibole replacing former pyroxene(?) probably originally contained in the original mafic magma can be observed (fig. 6) evidencing that an equilibrium of the mineralogical assemblage of the mafic magma once entrained into the thermodynamically and geochemically different felsic magma was attained.

Stop 5:

Sant'Andrea

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From the main road, Zanca village, down to S. Andrea village. S. Andrea area is probably the best place in Elba in which spectacular magma mingling/mixing phenomena between acid and basic magmas can be observed. The outcrop is literally "infested" by a huge amount of mafic microgranular enclaves (MME) dispersed in the granitoid host rock (fig. 1). MME range in size from few centimetres to two or more meters across. The sub-spherical shape of some MME gave rise to the informal name of this outcrop commonly referred to as "palle nere di S. Andrea" (literally, S. Andrea black balls). The outcrop is also valuable for the presence of large amounts of K-feldspars megacrysts belonging to the host granitoid magma whose size reaches up to 10-15 cm across.
The contemporaneous presence of MME and K-feldspars megacrysts makes this outcrop one of the best places to observe and investigate in detail mass transfer processes during magmas interaction.

Figure 1 Stop 5 - General view of part of Sant'Andrea outcrop showing the presence of large amounts of MME hosted within the granitoid mass.

Contacts between MME and host rock range from sharp to gradual and, commonly, transfer of the host magma into enclaves is observed under the shape

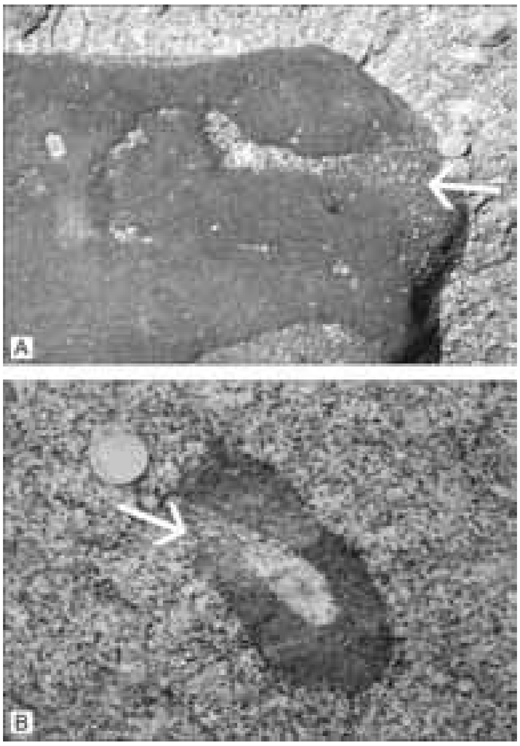

Figure 2 Stop 5 - A-B) Transfer of leucocratic material from the host magma to the MME by infiltration channels. In (B) the presence of a K-feldspar megacryst in the MME at the end of the infiltration channel indicates that it has been responsible for the disruption of the enclave boundary allowing the host magma to infiltrate.

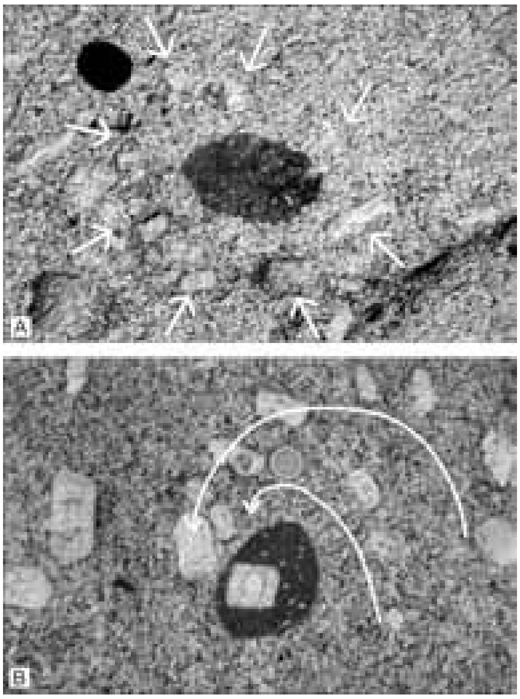

Figure 3 Stop 5 - A) Corona of K-feldspar megacrysts around a MME: B) vortex-like flow path followed by K-feldspar megacrysts around a MME.
In (B) note the resorption texture of the K-feldspar megacryst within MME.

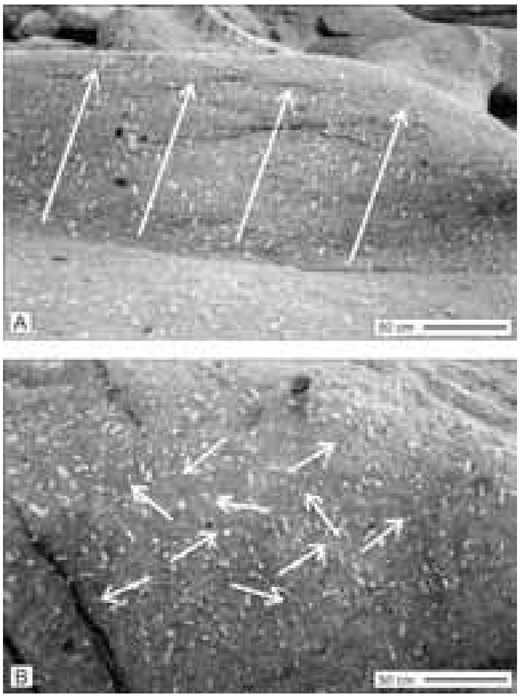

Figure 4 Stop 5 - Different flow fields at Sant'Andrea outcrop evidenced by the orientation of K-feldspar megacrysts. A) laminar flow field; B) random flow field.

of leucocratic channels cross-cutting the enclave boundary and propagating towards the core region of MME (e.g. fig. 2A).
Typically, K-feldspar megacrysts are associated with the presence of channels of the acid magma within enclaves (e.g. fig. 2B). Megacrysts position within enclaves suggests that they may have been responsible from the disruption of MME boundaries allowing the consequent transfer of host magma (fig. 2B). K-feldspar megacrysts are also good dynamical markers that may help to identify the structure of flow fields during magmas interaction. Often K-feldspar coronae are found around MME indicating circular or vortex-like fluxes (fig. 3A and B).
In some cases, vortex-like flow structures terminate against MME in which transfer of one or more K-feldspar megacrysts occurred (fig. 3B). K-feldspar megacrysts occurring within enclaves typically display disequilibrium textures evidenced by a resorbed core in which biotite crystals are included.
The evolution of flow structures, evidenced mainly by K-feldspar megacrysts and, in lesser amount MME, can be followed for several meters generating a wide variety of magmatic flows. In some cases megacrysts are alined in swarms suggesting laminar flows of the magmatic masses (fig. 4A), whereas, in other cases, no univocal direction can be detected (fig. 4B).
In this latter case megacrysts are randomly distributed suggesting more turbulent dynamics. The contemporaneous presence of such kind of flow patterns suggests that different coexisting dynamics (laminar and turbulent) may have governed the magmatic system inducing different mingling/mixing intensities between the basic and the acid magma.
Sant'Andrea rocks constitute an outstanding natural laboratory to understand the mechanisms and dynamics developing during magmas interaction.

Stop 6:
Punta Cotoncello

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At Punta del Cotoncello a dyke of leucocratic facies crosscuts the main Sant'Andrea facies (fig. 1).
The Cotoncello dyke has fine-grained groundmass and lower pheno-megacryst content with respect to Sant'Andrea granite facies. The Cotoncello dyke is the only occurrence in Elba of a high 87Sr/86Sr crust-derived magma. The contact shows a complex geometry, owing to the interplay of brittle and plastic relative behaviour of the intruding dyke and the host Sant'Andrea crystal mush. Clusters and trails of K-feldspar megacrysts, along with megacryst-laden schlieren are common in the area (fig. 2). Size and abundance of mafic microgranular enclaves are lower than observed in Sant'Andrea outcrop.

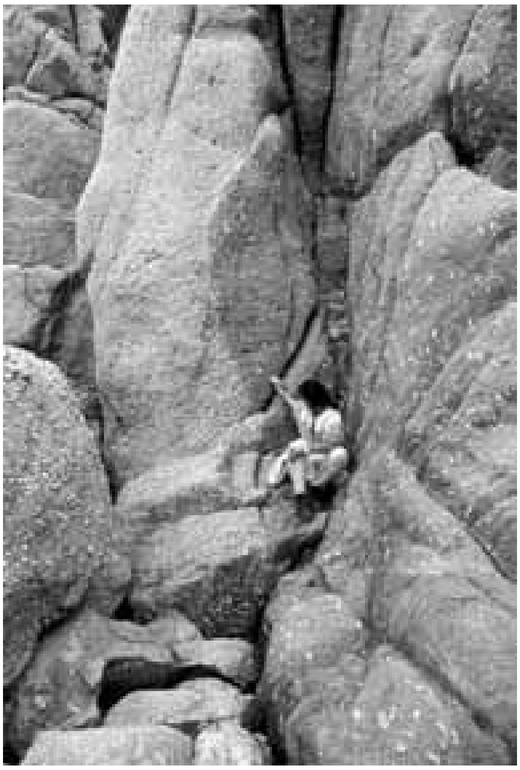

Figure 1 Stop 6 - Leucocratic facies crosscutting the main Sant'Andrea facies.

Stop 7:

Orano Dykes

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This stop, situated a few hundred meters NE of Orano village, allows us to examine NS orientated late melanocratic dykes cutting the Monte Capanne pluton. Similar dykes occur at Piaggia San Andrea and at the Poggio car park stop, where their injection together with a set of leucogranite dykes is discussed.
The Orano Dykes have a monzogranitic composition (67.6% SiO_2) but are significantly darker in colour than the porphyritic host MF (fig. 1). Resorbed K-feldspar megacrysts are abundant within the dykes and are clearly orientated along the strike (fig. 1). Sharp contacts are observed with the host (fig. 1 and 2). In some places, the dykes cut across K-feldspar megacrysts (fig. 2). Dextral shearing can be deduced, as evidenced by a left-stepping geometry within the

Figure 2 Stop 6 - Interplay between brittle and plastic behaviour of the intruding dyke and the host Sant'Andrea crystal mush.

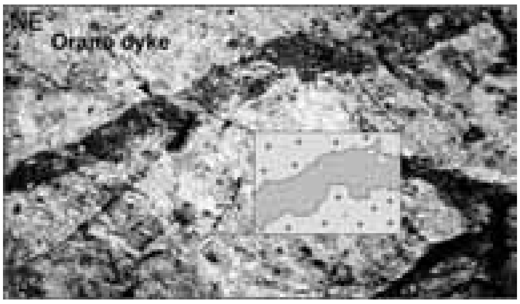

Figure 1 Stop 7 - Detail of the Orano dykes. Note the presence of both sharp and crenulated contacts along the margins of the dyke, as well as the re-orientation of corroded K-feldspar megacrysts within the dyke.

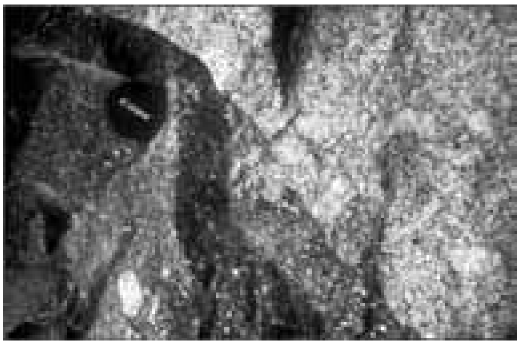

Figure 2 Stop 7 - Detail of a host/dyke contact in a Orano dyke. Note the abundance of plagioclase phenocrysts in the dyke and the presence of K-feldspar megacrysts in both the dyke and host, and the dyke cutting across one megacryst of the host.

dyke (a feature that can also be seen in Piaggia San Andrea). Locally, the magma of the dyke penetrates into the host along small fractures. These observations clearly point out the late occurence of these dykes relative to the Monte Capanne pluton, as opposed to their being syn-plutonic dykes. In detail, though sharp, the contact between the host and the dyke is irregular and crenulated, suggesting plastic behaviour during emplacement. Centimeter-sized embayments are visible all along the dyke margins (fig. 1), suggesting that the host was not totally solidified when the dyke intruded.

The mineralogy of the dyke chiefly consists of plagioclase, alkali feldspar and biotite as main phases, with apatite and zircons as accessory phases. The texture is strongly porphyritic. Phenocrysts are mostly plagioclase, biotite and subordinate K-feldspar megacrysts in a fine-grained, sometimes fluidal (fig. 3A), groundmass, which mostly consists of feldspar, quartz and biotite microcrysts (fig. 3A).

K-feldspar megacrysts display multiple evidence of resorption, with either rounded crystal faces (fig. 1 and 2) or with plagioclase mantles (Rapakivi texture). Quartz ocelli (2 to 10 mm) are also abundant, and are sometimes surrounded by a complex reaction rim consisting of a very fine intergrowth of biotite, feldspar and unidentified fibrous minerals. Similar ocelli are commonly observed in the MF and its MME. Plagioclase phenocrysts are abundant and display a great variety of textures. Several populations of plagioclase can be distinguished:

- unresorbed oscillatory zoned plagioclase phenocrysts (3 to 10 mm) similar to those observed in the host monzogranite.

This type of plagioclase often exhibits a

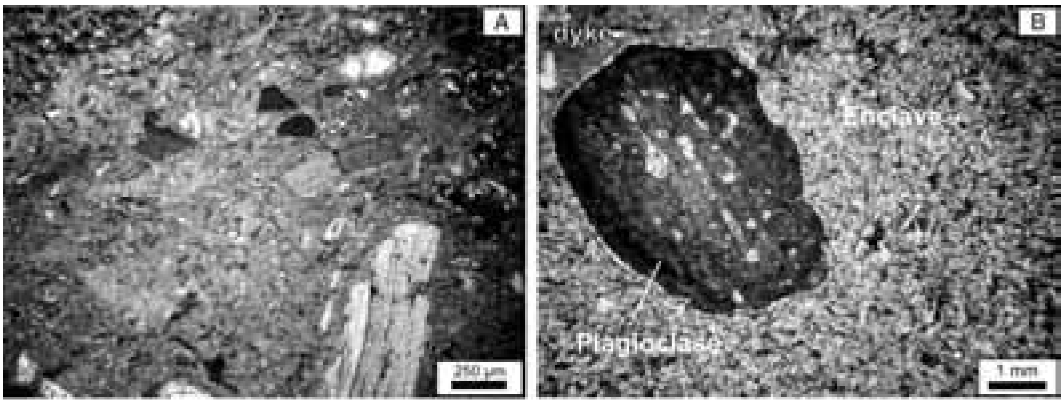

Figure 3 Stop 7 - (A): fine-grained fluidal porpyhritic texture of the Orano dyke with biotite phenocrysts; (B) "dusty" plagioclase phenocryst cutting across the dyke/enclave interface.

glomeroporphyritic texture;
- strongly zoned dendritic phenocrysts (< 1 mm), often exhibiting a patchy-zoned core;
- phenocrysts surrounded by a mantle of finely-intergrown biotite, apatite and two compositionally distinct plagioclase phases. Sometimes, the whole plagioclase phenocrysts exhibits this particular texture (fig. 3B), which is exclusively encountered in Orano dykes. They correspond to the "dusty" or "fritted" plagioclase which are common in a volcanic environment where a sodic plagioclase is immersed and dissolved in a more basic magma.

Figure 1 Stop 8 - General view of a section across Spartaia outcrop.

Mafic microgranular enclaves are common within the dykes and are often coarser grained than the host dyke (fig. 3B). Their mineralogy and textures are similar to the enclaves found in the host monzogranite. However, microgabbroic mafic enclave in one Orano dyke, with a mineralogy mostly consisting of plagioclase, quartz, biotite, amphibole and pyroxene can be also found. Amphibole has not been observed in Orano dykes, but it is worth noting that actinolitic amphibole (replacing former pyroxene) commonly occurs in Orano dykes observed at other localities (Poggio; see stop n. 9).

Overall, the late Orano dykes display multiple petrographic evidence of hybridisation and crystal exchange between a mafic mantle-derived magma and a granitic crystal mush.

Stop 8:
Spartaia

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From the Hotel Desirée, walk on the western side of the inlet. At the tip of the small peninsula, on a flat surface and some vertical cliffs, structures and mineralogy of metasedimentary rocks can be observed (fig. 1).

The outcropping rocks are referred to as the Ligurian (Complex IV of Trevisan) or the Ligurian-Piedmontese (Punta del Timone Sub-Unit) successions. The metasediments of the Spartaia area are represented mainly by irregularly alternating brownish to dark gray metapelites, dark gray to greenish ± siliceous marbles and calcschists, metasiltstones/metarenites and thin-bedded siliceous levels. The main metamorphic overprint is from contact with the Monte Capanne pluton, which led to the formation of diopside, wollastonite, vesuvianite.

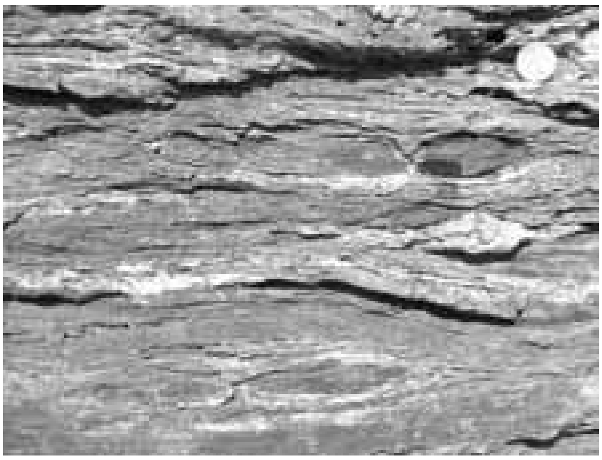

Figure 2 Stop 8 - Brittle deformation with formation of boudins of silicate-rich layers.

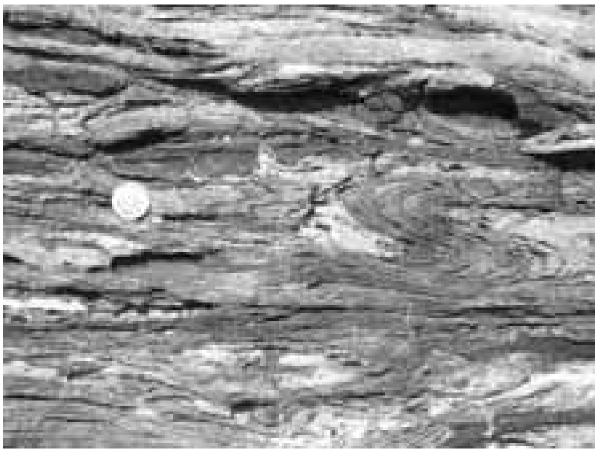

Figure 3 Stop 8 - Ductile deformation in carbonate layers flowing and folding around brittle boudins.

Figure 4 Stop 8 - Folded Ligurian metasediments crosscut by an aplitic dike along the Spartaia coast.

The silicate-rich layers show evidence for brittle deformation with formation of boudins (fig. 2), while ductile deformation can be seen in carbonate layers, that flows and fold around brittle boudins (Fig. 3).

These features are typical of deformation contemporaneous to thermal metamorphism. The pre-granitoid tectono-metamorphic framework of these rocks is particularly evident in correspondence of the marble and metalimestone levels which are deformed into syn- metamorphic isoclinal to tight folds whose axes plunge to NE or to SW. Moreover, Neogene aplitic dikes locally crosscut the above-said tectono-metamorphic framework of the Ligurian rocks (fig. 4). At the microscope, but even at the meso-scale, the static thermometamorphic blastesis (e.g. garnet, etc.) often clearly post-dated the main foliation and the fold hinges.

The genesis of these structures are matter of debate. In fact, they could result from one or more of the following processes: (i) inherited Alpine-Apenninic compressive deformation, (ii) syn-intrusive deformation linked to Monte Capanne pluton emplacement, (iii) to crustal extension in the northern Tyrrhenian area.

Stop 9:

Montecristo Island

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The steep profile of the Montecristo Island can be observed on clear days from the southern coast of Elba Island, but a better view is available when approached by boat (Fig. 1).

Globular masses of Darker varieties of the Montecristo monzogranite occur as globular masses suspended in the more typical paler variety, with both containing microgranular mafic enclaves (Fig. 2).

Walking from the wharf of Cala Santa Maria to the south side of the bay, the Montecristo monzogranite can be observed with K-feldspar and quartz megacrysts, along with scattered mafic microgranular enclaves. Pseudotachylyte veins, sometimes with

Figure 1 Stop 9 - Montecristo Island seen looking south.

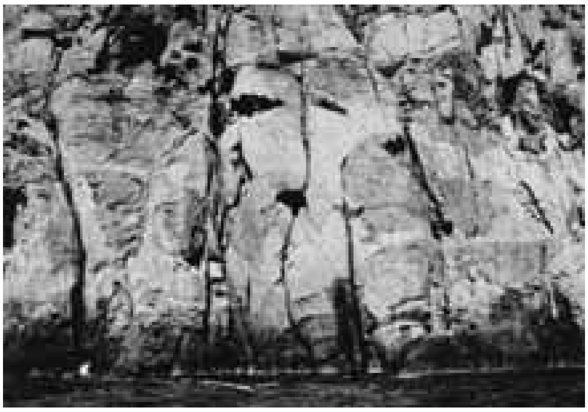

Figure 2 Stop 9 - Globular masses of darker Montecristo monzogranite (maximum dimension 10 m) in the more typical paler variety (Cala Giunchitelli).

tourmaline mineralisation, are also found in this area (Fig. 3).

A small roof pendant of thermally metamorphosed mafic-ultramafic rocks of the ophiolite host rock is exposed nearby on the coastal cliff between Cala Santa Maria and Cala Mendolina. Some hundreds of metres to the south-east, a thick, grey porphyritic dyke crosscuts the main granite.

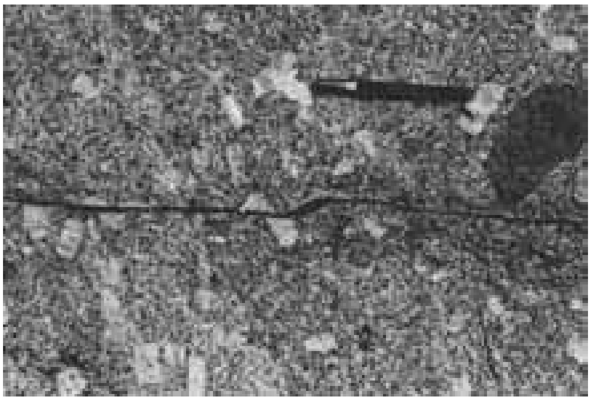

Figure 3 Stop 9 - Varieties of Montecristo monzogranite in sharp contact (trending diagonally from top to bottom in the left half of the photo). Note the crosscutting left-lateral pseudotachylyte. Pen length = 15 cm.

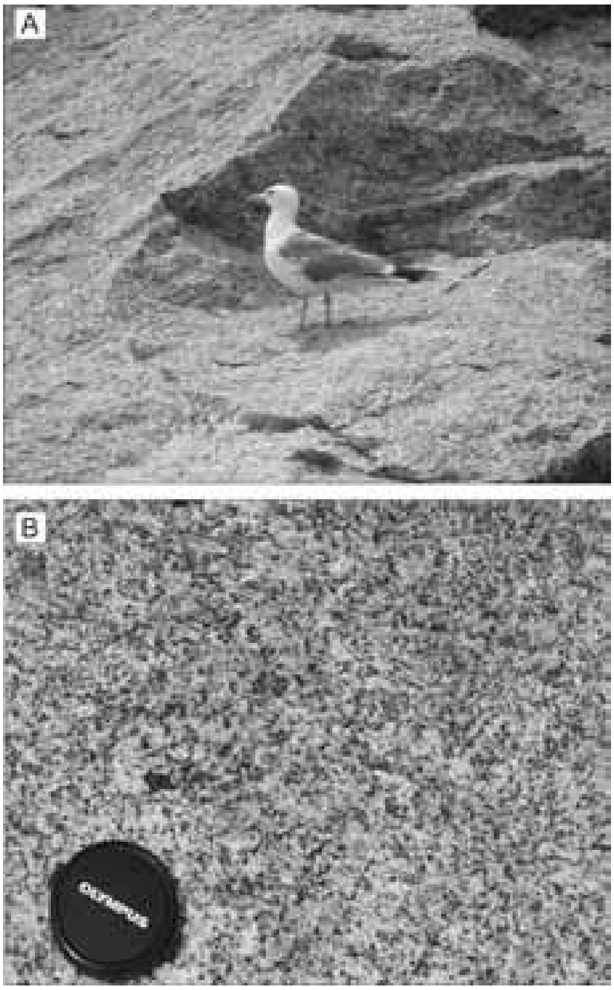

Figure 1 Stop 10 - A) General view and (B) detailed view of the fine-grained facies of Giglio Porto outcrop.

Stop 10:

Giglio "Porto"

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This stop focuses on a section of the Giglio Island granite cropping out close to the village of Giglio Porto. In this outcrop different facies constituting the Giglio granitoid mass coexist. The "normal facies" is characterized by an homogeneous medium-grained mass (fig. 1A and B) in which can be macroscopically recognised quartz, plagioclase, K-feldspar, biotite and quite abundant tourmaline cloths.
This facies is locally very rich in metamorphic-restitic xenoliths that give to the outcrop the aspect of a "leopard skin" (fig. 2).

Together with xenoliths, magmatic enclaves (Mafic Microgranular Enclaves, MME) are also abundant (fig. 3).
Generally they exhibit rounded/ovoid shape (fig. 3), but more complex shapes from amoeboid to elongated can be also observed. Although the grain size of MME is always smaller than the host granitoid mass, in most cases it is possible to observe an internal variation of grain size that increases progressively from the margin to the core of MME.
Spatially associated and intercalated with the medium grained facies of the granitoid mass are coarser grained facies (fig. 4A). They appear to be more leucocratic and this feature is due to the presence of large crystals of K-feldspar that appear to be in poikilitic texture with the other phases (fig. 4A). Commonly K-feldspar megacrysts contain large tourmaline nodules (up to 3-4 cm across) that give to the rock a "patchy"

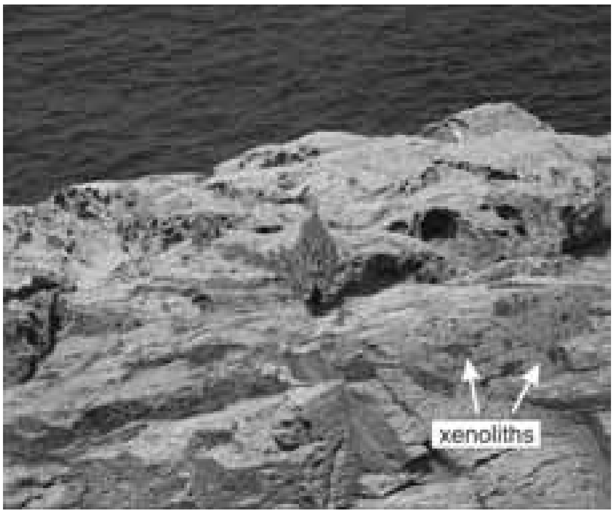

Figure 2 Stop 10 - "Leopard skin" aspect of the xenoliths-rich fine-grained facies

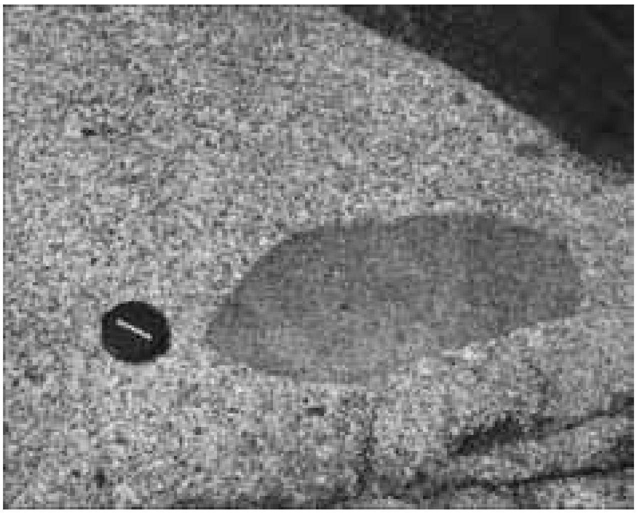

Figure 3 Stop 10 - Example of Mafic Microgranular Enclave (MME) with ovoid shape.

aspect (fig. 4B). The leucocratic facies is less rich in both xenoliths and MME with respect to the fine grained facies.

The overall interest of the outcrop resides on the close spatial association of the different facies and the occurrence of the different enclaves (xenoliths and MME). The fact that the two facies fade and inter-digitate one into the other highlights the problem of their contemporaneous evolution in a magmatic system in which interaction processes between felsic and mafic magmas occurred.

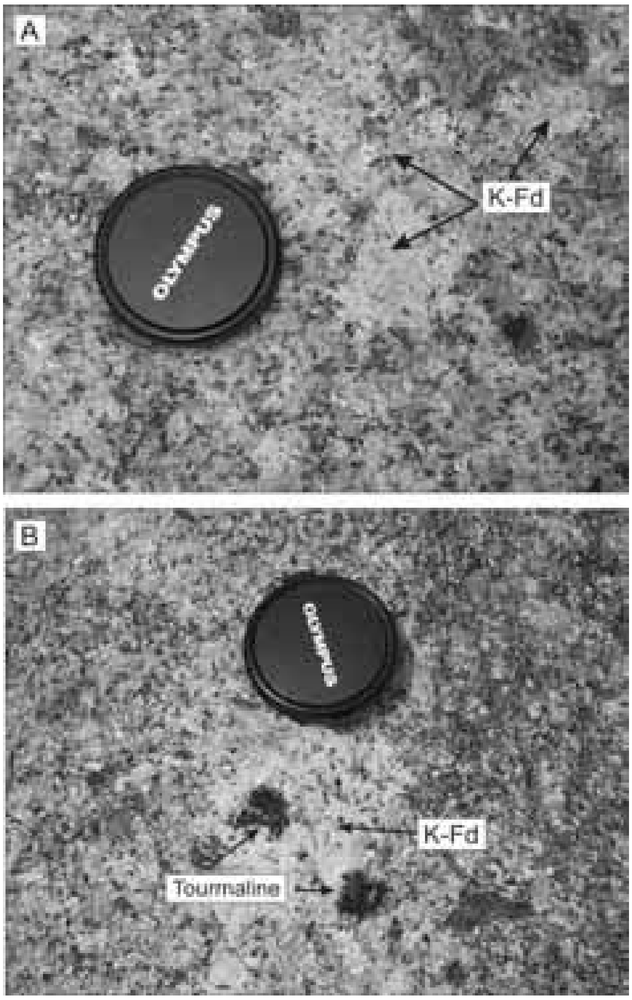

Figure 4 Stop 10 - A) Coarse-grained leucocratic facies of the Giglio Porto granitoid showing large poikilitic crystals of K-feldspar;
B) large crystal of K-feldspar occurring in the leucocratic facies including nodules of tourmaline.

Stop 11:

Botro ai Marmi

Andrea Dini

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The visit at the Botro ai Marmi quarry starts from the lower, exploited, levels where the granite crop out (fig. 1). This "leucocratic" granite is the product of a strong late-magmatic, hydrothermal event that removed Fe, Mg and added K. We can observe also many veins filled by quartz, chlorite, Pb-Zn-Fe sulfides. The very low Fe-Mg content, coupled with a high K concentration makes this granite exploitable as a high-quality raw-ceramic material.

The path along the western quarry edge drive to the upper levels, where thermometamorphic rocks and skarn are well exsposed. Bodies of coarse grained marble including large scapolite, diopside crystals, as well as vesuvianite-garnet masses are widespread at these levels. Both the skarn-thermometamorphic aureole and the granite below the contact are crosscut by a two generations of hydrothermal veins: the first system carries adularia, quartz, scapolite, diopside, allanite, fluorite, scheelite, arsenopyrite, pyrrhotite, whereas the second system is similar to that observed at the lower levels (chlorite, quartz, Pb-Zn-Fe sulfides).

Figure 1 Stop 11 - General view of Botro ai Marmi quarry.

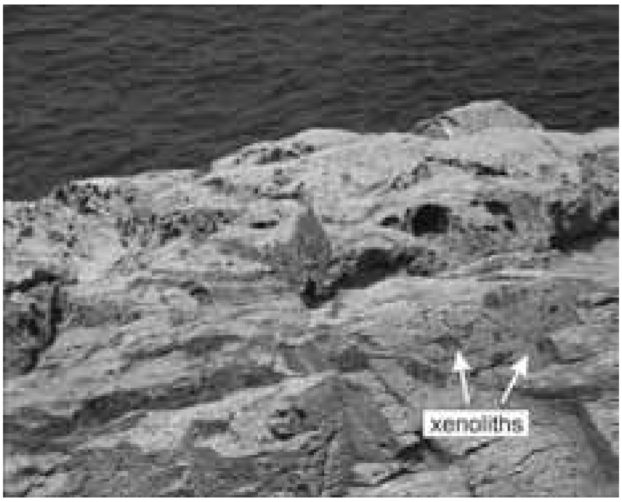

Figure 2 Stop 11 - "Leopard skin" aspect of the xenoliths-rich fine-grained facies.

Stop 12:
Temperino Mine
Andrea Dini
CNR, Istituto di Geoscienze e Georisorse, Via Moruzzi, 1, 56124, Pisa, Italy

The Temperino ore deposit is a classic example of a Cu-Pb-Zn skarn deposit hosted in limestone, and genetically linked to shallow-level porphyritic intrusions. During the visit in the underground works we can observe some good exposures of the typical hedenbergite-ilvaite-quartz skarn that include disseminations of pyrite and chalcopyrite. The Temperino tunnel, now used for the touristic visit, was opened during the 19th century to exploit, at a lower level, a skarn mineralization exploited yet by Etruscans. So, in several places we observe the occurrence of old refills made up of small boulders and stones cemented by supergenic gypsum, native copper, azurite, and malachite.

Finally, a short trip to the "Earle Shaft" area give us the possibility to observe the two porphyritic rocks strictly related to the skarn genesis (Porfido Giallo e Porfido Verde), and other examples of skarn textures and mineralogy (fig. 1).

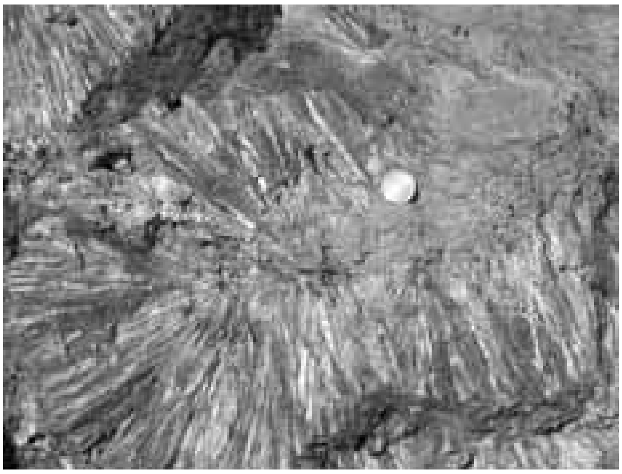

Figure 1 Stop 12 - Detailed view of hedenbergite radiate crystals belonging to the skarns occurring in the area of Temperino mine.

Stop 13:
San Vincenzo (Acqua Calda quarry)
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This stop focuses on "Acqua Calda" (literally, "worm water") quarry where S. Vincenzo volcanites crop out. The outcrop consists of a quite large section (30-50 m across) of a magmatic mass in which two overlapping large-scale dynamical structures can be recognised. The first is given by sub-vertical columnar jointing and the second is represented by folding structures (fig. 1). Both structures have been presumably generated during magma extrusion and emplacement. The columnar jointing can be related to the rapid quenching of the magma during extrusion whereas the folding structures are the result of flow after magma was extruded. The morphology of the folding structures suggest a slow spreading of the highly viscous rhyolitic magma and argues in favour of the hypothesis that the outcrop represents a section of a lava dome.

From a petrographic point of view, rocks can be divided into two main varieties with microcrystalline (fig. 2A) or glassy (fig. 2B) ground mass. In some samples micropegmatitic textures can be observed (fig. 2C). One interesting aspect of these rocks is the strong disequilibrium textures exhibited by most mineralogical phases as, for instance, inverse and oscillatory zoning in plagioclase crystals (fig. 2A) and strongly anhedral crystals showing resorption gulfs (fig. 2D and E).

The outcrop is also worth noting because of the occurrence of cordierite crystals suggesting that acid magmas cropping out in the area be the result of anatexis of crustal rocks (garnet bearing micaschists).

Figure 1 Stop 13 - Section of the "Acqua Calda" quarry showing columnar jointing and folding structures.

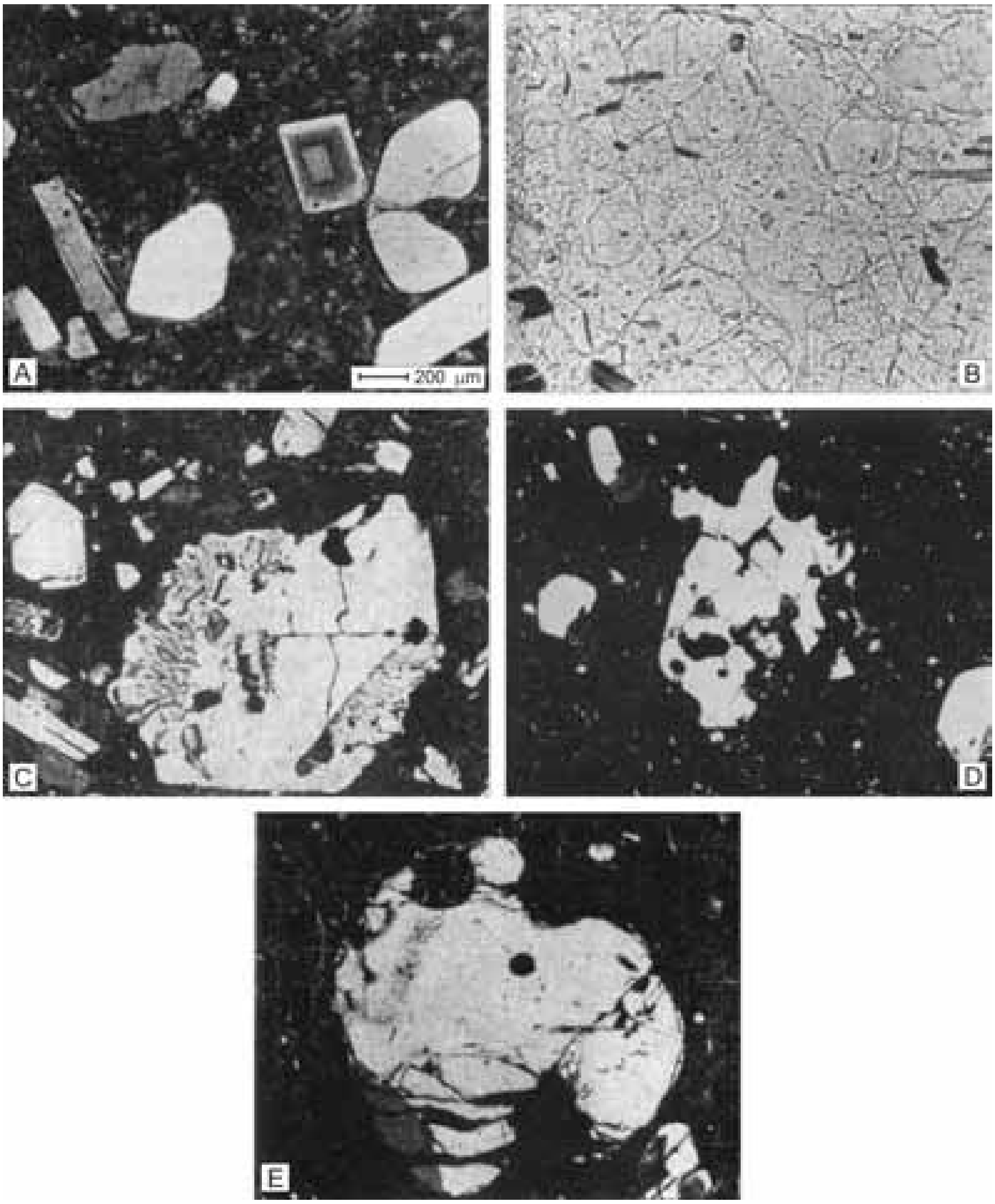

Figure 2 Stop 13 - Examples of rocks having microcrystalline (A) and glassy (B) ground mass; C) micropegmatitic texture; crystals of quartz (D) and cordierite (E) showing resorption gulfs.

Stop 14:

Roccatederighi

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A cluster of rhyolitic endogenous and exogenous lava domes crops out in the area of Roccatederighi village. Roccatederighi itself is built over such domes (fig. 1A). The outcrop has a very irregular morphology related to the fact that the original morphology of domes has been in part disrupted by successive effluxes of lava from the same vents and by the action of erosion processes (fig. 1B).

The rock has both a glassy groundmass containing crystals of quartz, K-feldspar (high-T sanidine), plagioclase, and biotite (fig. 2A), and a

Figure 1 Stop 14 - A) Panoramic view of the tower of Roccatederighi village built over the rhyolitic lava domes; B) general view of Roccatederighi outcrops.

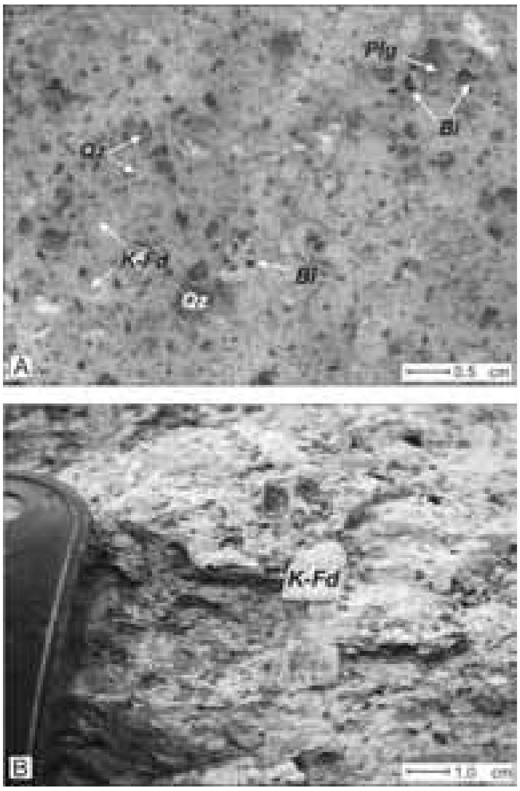

Figure 2 Stop 14 - A) Macroscopic view of a sample from Roccatederighi showing the glassy groundmass in which phenocrysts are immersed; B) detailed view of a sample from Roccatederighi showing the microcrystalline groundmass with the presence of K-feldspar (sanidine) megacrysts.

microcrystalline groundmass with the presence of K-feldspar (sanidine) megacrysts that in some cases reach sizes up to 5-10 cm across (fig. 2B).

Commonly minerals are strongly fractured and in some cases schlieren-like structures can be observed (fig. 3) evidencing a strong friction exerted by the highly crystalline and viscous magma on mineral phases during flow.

The peculiarity of Roccatederighi rocks is the presence of magmatic cordierite crystals. Cordierite occurs as euhedral-subhedral (fig. 4A) to anhedral (fig. 4B) crystals in some cases showing a dusty aspect because of alteration into pinnite crystals which are often oriented along cracks. On the basis of Fe/Mg distribution coefficients, euhedral cordierite can be considered as magmatic origin, whereas the anhedral variety as restitic. The occurrence of cordierite

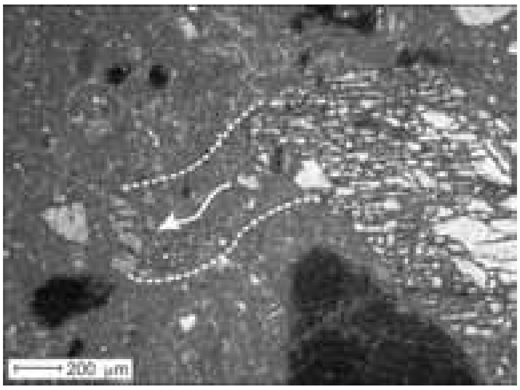

Figure 3 Stop 14 - Schlieren-like structure generated by the disruption of a K-feldspar (sanidine) phenocryst; dashed lines and arrow indicate the possible direction of the flow.

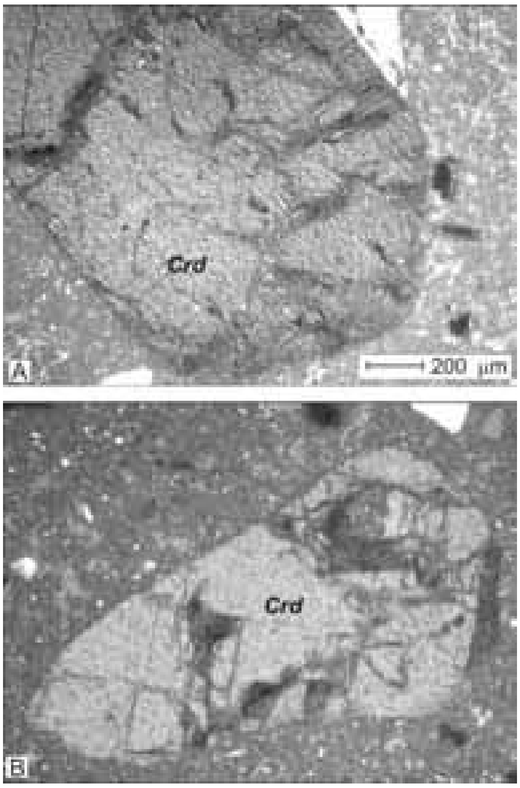

Figure 4 Stop 14 - A) and B) phenocrysts of cordierite having euhedral-subhedral and anhedral morphology, respectively.

crystals in Roccatederighi rocks led to hypothesize that these rocks were pure anatectic melts possibly generated by melting of garnet-bearing micaschists.
Interesting is also the occurrence of disequilibrium textures of mineral phases, exemplified by rounded or embayed crystal morphologies (fig. 5A and B). The lacking of any evidence of magmatic interaction processes leads to hypothesize that these disequilibrium textures may be the result of an increase of volatile content in the magma associated to pressure drop during ascent.

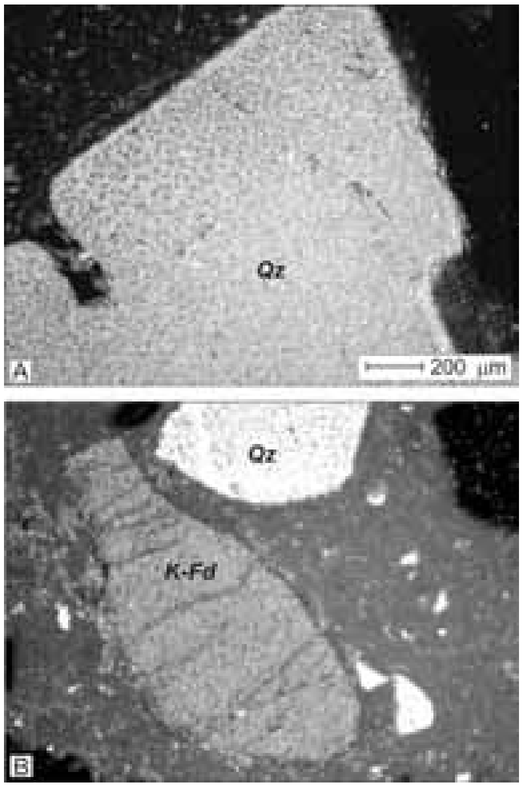

Figure 5 Stop 14 - Examples of crystals showing disequilibrium textures; A) crystal of quartz with embayments; B) corroded crystals of quarz (upper part) and K-feldspar (sanidine).

Back Cover:
field trip itinerary

32nd INTERNATIONAL GEOLOGICAL CONGRESS

FIELD TRIP MAP

Edited by APAT